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PSEUDO-NOISE CODE HOPPING METHOD AND APPARATUS

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CROSS-REFERENCE TO RELATED APPLICATIONS

This application is related to copending U.S. Application
5 No. _____ (Attorney Docket No. 907.0005.U1(US), filed
_____. This disclosure of this Non-provisional Patent
Application is incorporated by reference herein in its
entirety.

BACKGROUND OF THE INVENTION

10 1. Field of the Invention

This invention is generally related to telecommunications
systems and apparatuses that employ spreading PN-codes
and, in particular, relates to methods and apparatus for
hopping PN-codes for mitigation of multi-user
15 interference in code division multiple access (CDMA)
systems.

2. Prior Art

Spread spectrum (SS) systems, which may be CDMA systems,
are well known in the art. SS systems can employ a
transmission technique in which a pseudo-noise (PN) PN-
20 code is used as a modulating waveform to spread the
signal energy over a bandwidth much greater than the
signal information bandwidth. At the receiver the signal
is de-spread using a synchronized replica of the PN-code.

There are two basic types of SS systems: direct sequence spread spectrum systems (DSSS) and frequency hop spread spectrum systems (FHSS).

5 The DSSS systems spread the signal over a bandwidth $f_{RF} \pm R_c$, where f_{RF} represents the center bandpass carrier frequency and R_c represents the PN-code maximum chip rate, which in turn is an integer multiple of the symbol rate R_s . Multiple access systems employ DSSS techniques when transmitting multiple channels over the same frequency
10 bandwidth to multiple receivers, each receiver having its own designated PN-code. Although each receiver receives the entire frequency bandwidth only the signal with the receiver's matching PN-code will appear intelligible, the rest appears as noise that is easily filtered. These
15 systems are well known in the art and will not be discussed further.

FHSS systems employ a PN-code sequence generated at the modulator that is used in conjunction with an m-ary frequency shift keying (FSK) modulation to shift the
20 carrier frequency f_{RF} at a hopping rate R_h . A FHSS system divides the available bandwidth into N channels and hops between these channels according to the PN-code sequence. At each frequency hop time a PN generator feeds a frequency synthesizer a sequence of n chips that dictates
25 one of $2n$ frequency positions. The receiver follows the same frequency hop pattern. FHSS systems are also well known in the art and need not be discussed further.

As noted, the DHSS system PN-code sequence spreads the data signal over the available bandwidth such that the
30 carrier appears to be noise-like and random, but is deterministic to a receiver using the same PN-code.

It is well known that the selection of PN-codes in CDMA systems is of critical importance. Ideal PN-codes are perfectly orthogonal in that the autocorrelation function for the PN-code has a large peaked maximum for perfect
5 synchronization of two identical PN-code sequences; and zero cross correlation between different PN-codes sequences.

Of the number of possible sets of orthogonal functions that can be used as PN-code generators, Hadamard
10 functions are recognized as being particularly well suited for their orthogonal properties. Hadamard functions can be described by Hadamard matrices with powers of 2 as ordinary numbers and are well known in the art. Other orthogonal systems can be derived from
15 Hadamard matrices by permuting the columns while still preserving the original orthogonal characteristics.

One such derivation technique is the application of Walsh functions. Walsh functions are a set of binary and
20 orthogonal waveforms that can be used for signal multiplexing purposes, and have long been recognized as having application to telephony. Reference in this regard can be had to an article entitled "The Multiplexing of Telephone Signals by Walsh Functions", by I. A. Davidson
25 in Applications of Walsh Functions, 1971 proceedings, Second Edition, Eds. R. W. Zeek and A. E. Showalter, pages 177-179.

Another technique for creating PN-codes which are
30 mutually orthogonal is to use a recursive construction technique defined by H. Hubner, "Multiplex Systems Using

Sums of Walsh Functions as Carriers", also in Applications of Walsh Functions, 1971 proceedings, Second Edition, pages 180-191. Reference in this regard can also be had to U.S. Pat. No. 5,571,761, entitled "System and
5 Method for Orthogonal Spread Spectrum Sequence Generation in Variable Data Rate Systems", by Klein S. Gilhousen.

In modular CDMA systems, such as cell systems where a base station controls what PN-codes are used, there are
10 functions for generating PN-codes that, for all practical purposes, are completely orthogonal. In multiple cell systems, however adjacent cells using a common frequency band may have PN-code sets that may not have low cross-correlation values.

15 Another source of interference between adjacent cells arises from a common method used to increase the data rate of a DS-CDMA system operating with a fixed PN-code-chipping rate. This method implements variable rate spreading PN-codes where very few chips modulate each
20 symbol in order to increase the effective symbol rate of the system, but at the expense of a decreasing spreading gain. The disadvantage of using the smaller spreading gains is that there will be instances where users in adjacent cells use PN-codes that are highly cross-
25 correlated for a given offset, resulting in potentially significant amounts of interference. In a DS-CDMA system where users are assigned fixed PN-codes, using the wrong PN-code at the wrong offset can result in significant
30 levels of adjacent channel interference for every transmitted symbol. Users in this situation would experience a much lower signal-to-noise ratio than other users in the cell. To combat this worst-case situation,

PN cover PN-codes are typically used in the adjacent cells, effectively scrambling the spreading PN-codes and reducing the frequency of perfect and highly correlated levels of interference. A cover PN-code would slightly
5 reduce the signal-to-noise ratio for all users with the aim of preventing any user with a severe degradation in signal-to-noise due to adjacent cell PN-code cross-correlation.

10 While the use of cover PN-codes appears attractive to solving the problem of worst-case adjacent channel interference resulting from high levels of PN-code cross-correlation, there are several disadvantages with using cover PN-codes.

15 First, cover PN-codes are difficult in application, as the cover PN-code must be applied to all CDMA channels, including the control and random access channels. This results in potentially longer and more complex
20 acquisition schemes and circuitry.

Another disadvantage that arises when applying a cover PN-code to the matrix of Walsh PN-codes is that the resulting Walsh PN-codes are unbalanced. This means that,
25 over any symbol period the number of +1 valued chips and -1 valued chips are not equal in most of the resulting PN-codes. A balanced PN-code is a desirable property since it implies that the PN-codes are orthogonal to any DC offset in the receiver of the signal. In other words,
30 if the chips are ± 1 millivolts in the receiver, but there is a 2 millivolt DC offset in the signal at the input of the despreader, then the despreader would have to multiply the ± 1 despreading PN-code with an input signal

having values of +3 and +1 millivolts. However, if the PN-code is balanced over a symbol, then the DC offset will not affect the despreading process.

5 Therefore, it is desirable to provide a method and system to overcome the difficulties with cover PN-codes and to mitigate the worst-case adjacent cell interference problem and provide several advantages not available with cover PN-codes.

10

SUMMARY OF THE INVENTION

The foregoing and other problems are overcome, and other advantages are realized, in accordance with the presently preferred embodiments of these teachings.

15 In accordance with one embodiment of the invention a PN code hopping method for mitigating cross-correlation interference is provided. The method includes the steps of storing a plurality of orthogonal PN codes in a memory device and pseudo-randomly accessing the memory device to
20 retrieve one of the PN codes. Each of the PN codes is associated with a useful life cycle and is used to spread a modulated data signal before the end of its useful life cycle when another PN code is pseudo-randomly retrieved.

In accordance with another embodiment the invention
25 includes a pseudo-noise (PN) code hopping device. The device includes a memory device for storing time limited PN codes and an addressable multiplexer coupled to the memory device. An address generator coupled to the multiplexer selects which time limited codes are to be
30 selected.

In accordance with yet another embodiment the invention is directed towards a PN code hopping system for mitigating cross-correlation interference between Direct Sequence-Code Division Multiple Access (DS-CDMA) users. The system includes two PN code-hopping modules. Each module includes a memory device for containing time limited PN codes and an addressable multiplexer. Their respective address generators address the addressable multiplexers to select the appropriate time limited PN code.

BRIEF DESCRIPTION OF THE DRAWINGS

The foregoing aspects and other features of the present invention are explained in the following description, taken in connection with the accompanying drawings, wherein:

Figure 1 is a block diagram of a system incorporating PN-code hopping features of the present invention;

Figure 2 is a block diagram of a homodyne DS-CDMA transmission system incorporating features of the present invention using spreading PN-code hopping with a look-up-table (LUT);

Figure 3 is a block diagram of a homodyne DS-CDMA transmission system incorporating features of the present invention using spreading PN-code hopping with an linear-feedback shift register (LFSR);

Figure 4 is a block diagram of a spreading PN-code hopping system incorporating features of the present invention using LFSRs for heterodyne DS-CDMA systems;

5 Figure 5 is a block diagram of a spreading PN-code hopping system incorporating features of the present invention using LUTs for heterodyne DS-CDMA systems; and

Figure 6 is a flow chart for one method for implementing
10 PN-code hopping features of the present invention in the system shown in Figure 1; and

Figure 7 is a graph of correlation of spread factor 32 (chips/symbol) spreading PN-code with a randomized set
15 with spreading factor 32.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Referring to Fig. 1, there is shown a circuit diagram
20 incorporating features of the present invention. Although the present invention will be described with reference to the embodiments shown in the drawings, it should be understood that the present invention could be embodied in many alternate forms of embodiments.

25 Referring now to Figure 7 there is a graph representing correlation relationships between a PN-code (not shown) in a given cell and PN-codes in an adjacent cell. As shown, if the given PN-code of one cell happens to correlate with an adjacent PN-code, for example code 26
30 of another cell, the cross-correlation peak is relatively high and results in undesirable interference between the users. PN-code hopping features of the present invention

allow the user to change the given PN-code on a symbol-by-symbol or block-by-block basis. Thus, the given PN-code correlates with all the adjacent PN-codes over a given time frame. This results in an averaging of interference as shown by the averaging line 71 in Figure 7. PN-code-hopping features of the present invention may be adapted to homodyne spreading (using a single PN-code) or heterodyne spreading.

Referring to Figure 1, one embodiment incorporating PN-code hopping features of the present invention is shown in circuit 90. Referring also to Figure 6 there is shown a flow chart for one method for implementing PN-code hopping features of the present invention in the system shown in Figure 1. The circuit 90 incorporates memory 91, multiplexer(s) (MUX) 93 and address generator(s) 92. The address generator 92 generates sequences, step 62, which pseudo-randomly select a spreading PN-code for a current symbol or block of symbols. The PN-codes may be prestored, step 61, or in an alternate embodiment, may be generated and stored dynamically. The address generator 92 may be implemented using, for example, a look-up table (LUT) or a linear-feedback shift register (LFSR). A base PN-code set containing base PN-code vectors (c_i 's) is shown in memory structure 91. Preferably the base PN-code set is constructed from orthogonal designs with the PN-code vectors of sets $(c_1 \dots c_p)$, $(c_{p+1} \dots c_{2p})$, ... $(c_{(n-1)p+1} \dots c_{np})$ being mutually orthogonal. The address generator 92 may be clocked at a hopping rate or predetermined or useful life cycle of the PN-codes, and outputs a $1 \times P$ vector of chips to modulate (or spread) the data, step 63. Once the useful lifecycle of the PN code has expired, step 64, the

address generator 92 again pseudo-randomly selects a PN-code from memory, step 62.

5 In alternate embodiments the address generator 92 may be any suitable address generator. Exemplary, but not limiting examples include linear-feedback shift registers or random access memories. In alternate embodiments the useful life cycle of a stored PN-code may be determined by a symbol rate or an integer multiple of a symbol rate.
10 To hop or change PN-codes every symbol, the address generator 92 clocks at the symbol rate of the transmission. The address generator 92 is preferably designed such that collisions (i.e. two users using the same PN-code) are avoided.

15 In practice a user's device is assigned to a particular set of PN codes and given an initial seed and/or phase which is the starting point from which the address generator pseudo-randomly selects (hops) one of the PN
20 codes. The set of assigned PN codes may be done at link establishment or may be predetermined and stored in the user's device. The initial phase is sufficient for both the transmitter and receiver to be able to recover (or despread) the data correctly. In a fixed-rate DS-CDMA
25 system the spreading PN-code set is preferably partitioned into hopped and non-hopped PN-codes and a PN-code-hopping pattern and hop duration is specified. The hop duration can be either the symbol rate (chipping rate / P) or multiple chips or some integer multiple of the
30 symbol rate. Hopping is not presently preferred in the middle of a symbol since orthogonality between users PN-codes could be compromised.

In a variable rate DS-CDMA system, users operate with a fixed chipping rate, but can choose spreading PN-codes with differing spreading gains in order to achieve different symbol rates. Typically, a minimum spreading gain is specified, for example, P_{\min} of 8 or 16, along with a maximum spreading gain $P_{\max} = n P_{\min}$. A variable rate spreading PN-code set is constructed from a base PN-code set having P_{\min} PN-codes. The variable rate spreading PN-code sets can be constructed using this base PN-code set via recursive techniques, or non-recursive techniques, as in U.S. Patent 6,091,760 the contents of which is incorporated herein by reference in its entirety to the extent that it does not conflict with the teachings contained herein.

In either construction, a single base PN-code with P_{\min} chips/symbol will form two orthogonal PN-codes with $2 P_{\min}$ chips/symbol, four orthogonal PN-codes with $4 P_{\min}$ chips/symbol and so. The base PN-code or "parent code" is present in each of PN-codes with higher spreading gain.

For the case of PN-code hopping applied to variable rate CDMA, one method for incorporating PN-code-hopping features of the present invention is to hop at a multiple of the symbol rate of the lowest symbol rate (or highest spreading gain). Thus, a user using a PN-code at P_{\min} would use his PN-code for k_n symbols, where $P_{\max} = n P_{\min}$, and a user using a spreading gain of P_{\max} would use his PN-code for $k=1,2,\dots$ symbols. In this manner the orthogonality between PN-codes is preserved, but users with small spreading gain are caused to hop PN-codes at a slower rate than users at the larger spreading gains.

Referring to Figure 3 there is shown one embodiment of a spreading PN-code generator for implementing the PN-code-hopping features of the present invention in a homodyne DS-CDMA system. A PN-code set C is stored in an $N \times SF$ binary matrix 26 with spreading PN-codes denoted by $1 \times SF$ vectors C^i , where i is the PN-code row index. Any suitable memory device, or devices, may be employed to retain the PN-code set C. Exemplary, but not limiting examples include random access memory (RAM) devices, and read-only-memory (ROM) devices. In addition, any suitable PN-code set C may be stored in the memory device. The PN-code set may be predetermined and pre-stored or may be dynamically determined based upon changing variables and/or conditions. An exemplary, but not limiting example may include a fail-safe response to a failure of one of the memory devices, thus requiring re-optimizing the PN-code based upon available memory.

The circuit 20 clocks the memory 26 at a rate of R_c , generating N chips corresponding to the k th column of the C matrix. In the preferred embodiment the N -chip values are parallel clocked out. In alternate embodiments the N -chips could be serially outputted on, for example a universal serial bus (USB) and converted parallel with a suitable serial-to-parallel device. The N -chip values are presented to an $N:1$ multiplexer 27, where the address of the MUX 27 is the PN-code index for the current symbol, k is a chip index ranging from 0 to $SF-1$, and l is a PN-code index ranging from 0 to $N-1$. The PN-code index is generated from a look-up-table (LUT) 22 of size $n \times P$ where P is the period of the PN-code hopping and n is a bit-width with $n \geq \log_2(N)$. The address of the LUT 22 is

generated by an up or down-counter 21 with both the LUT and counter operating at $SF \cdot R_c$. In an alternate embodiment an operation, such as a modulo operation, may be performed by the modulo operator 24 on the LUT 22 output to ensure that a valid PN-code index is generated with $K \leq N$. The modulo operation can be avoided if the LUT 22 values are sized appropriately, or if K is a power of two, in which case limiting 1 to $n = \log_2(N)$ bits performs the modulo operation. Note, that if $K < N$, then some of the PN-codes (e.g. the PN-codes with $1 > K$) may be omitted from the hopping. For adjacent cell/sector isolation, adjacent cells/sectors may use LUTs containing different hopping patterns.

In an alternate embodiment un-hopped PN-codes may be desirable for random access channels or to remove certain CDMA channels from the hopping operating. When the hop_enable switch 25 is turned off the transmitted spreading PN-codes are un-hopped for that particular CDMA channel. These "unhopped" CDMA channels may be used, for example, for random access or pilot channel purposes.

In an alternate embodiment it may also be desirable to reset the hopping in accordance with link layer framing boundaries. Thus, a reset is shown for the up/down counter 21 (RESET).

Referring now to Figure 3 there is shown another embodiment for implementing the PN-code-hopping features of the present invention in a homodyne DS-CDMA system with an LFSF 36. The advantage of the LFSR 36 is that very long, random hop periods may be produced without large amounts of memory. The LFSR sequence is determined

by the initial value of the LSFR (e.g. LFSR seed) and the feedback polynomial $p(D)$. For an M-bit binary LFSR with feedback polynomial $p(D)$, the period of the sequence L is less than 2^M . For adjacent cell/sector isolation, adjacent
5 cells/sectors may use different feedback polynomials and seeds. For long LFSRs, it is sufficient to use a feedback polynomial with a long period and use different phases (e.g. seeds) for the different cells/sectors.

10 In alternate embodiments, a LFSR or other suitable device may be used to randomly populate a LUT. Such an arrangement captures the fast response feature of a LUT while ensuring that a valid PN-code index is generated by the LUT. Another advantage is that the LFSR seed value
15 and/or feedback polynomial can be changed as required to repopulate the LUT.

To maintain orthogonality between in-cell users, the in-cell users should preferably use the same hopping pattern
20 (e.g. LUT or LFSR + seed) but be given unique initial PN-code indices (l_0).

In an alternate embodiment, the pseudo-random nature of selecting an input address of the addressable multiplexer
25 may include the step of constraining the pseudo-random selection to select the input address based upon previously selected PN codes. For example, it may be desirable to maintain code balance to a predetermined tolerance. The address generator may then be constrained
30 to pseudo-randomly select the next PN code from an area of the memory device with PN-codes of known balance.

In yet another embodiment the address generator may include a completely random, i.e., not deterministic, selection of PN codes. The random selection pattern is captured by the address generator and transmitted to a receiver ahead of the hopped PN-code modulated data signal.

Referring now to Figure 4 there is shown an alternate method for incorporating PN-code hopping features of the present invention in a heterodyne spreading system 40. In heterodyne spreading a PN-code set is constructed from two base sets, a modulation matrix 41 and a base PN-code set 45. The constructed PN-code set is adapted for variable-rate DS-CDMA such that users operating at different data rates retain orthogonality. The variable-rate DS-CDMA operates with a minimum spread factor SF_{min} and a maximum spread factor SF_{max} . Letting $L = SF_{max}/SF_{min}$, then L is preferably an integer and the modulation matrix has dimension $L \times L$. Letting $P = SF_{max}/L$, then P is also preferably an integer and the base PN-code matrix has dimension $P \times nP$ where n is a PN-code order number.

It should be noted that heterodyne spreading alone, without the PN-code hopping features of the present invention, has the property that different PN spreading PN-codes are used for different symbols. Yet, disadvantageously, at the lowest spreading factor (SF_{min}), the spreading PN-codes repeat with period nL symbols. At the next spreading factor ($2 SF_{min}$), the spreading PN-codes again repeat with period $nL/2$ symbols. At the largest spread factor (SF_{max}), the spreading PN-codes repeat with period n symbols.

Because the spreading PN-codes repeat, even with heterodyne spreading, there is a likelihood of adjacent cell/sector interference. However, PN-code hopping features of the present invention may be implemented to
 5 increase the apparent randomness of the PN-code sequences. Referring still to Figure 4, the row indices of the modulation matrix 41 and the base PN-code set 45 are varied to implement PN-code hopping. Figures 4 and 5 show the circuits for implementing PN-code hopping
 10 features of the present invention in a heterodyne spread system using LUTs and LFSRs, respectively. In alternate embodiments the heterodyne spread system could be adapted to use a LUT and a LFSR as represented in Figure 5 for generation of the row indices.

15 Referring still to Figure 4 and 5, the modulation matrix 81,41 row index hops with a period of P_1 while the base PN-code set matrix hops with a period of P_2 . A total of $K_1 \leq L$ rows of the modulation matrix and $K_2 \leq P$ rows of the
 20 base PN-code set matrix are used for hopping. The total hopping period is related to n , P_1 , P_2 . Referring to Figure 5, one method of PN-code hopping is sequential hopping, where the address generators 87,802 are controlled by up/down counters 86,801, respectively and
 25 may be individually seeded by integers $0 \dots P-1$. Each user starts with unique seeds to avoid collisions with the seeds representing a pointer into the PN-code set tables.

Figures 4 and 5 show hopping of both the modulation
 30 matrix and the base PN-code set. In alternate embodiments, hopping of only the modulation matrix or the base PN-code set could be implemented in a heterodyne spreading system.

In a variable-rate DS-CDMA system using heterodyne spreading, it may be preferable to disable hopping of the modulation matrix since the variable-rate spreading factor identifies which rows of the modulation matrix may be used to maintain orthogonality. For example, channels at spread factor SFmin may use only row 0 of the modulation matrix. Channels at spread factor $2 \times \text{SFmin}$ may use only rows 0 and 1 of the modulation matrix. A hopping PN-code may hop into a forbidden row and thereby reduce orthogonality.

It will be appreciated that the PN-code hopping features of the present invention provide several advantages over the prior art.

First, with the PN-code hopping features of the present invention, the PN-codes used for random access and control can be omitted from the hopping sequence. These non-hopped PN-codes can be acquired with reduced acquisition time and complexity.

Next, PN-code hopping preserves the balance in a PN-code set. Balanced PN-codes may be important for orthogonal DS-CDMA systems since balanced PN-codes mitigate DC biasing problems in the receiver. It will be further appreciated that the PN-code hopping features of the present invention will allow the use of sets of preferred PN codes containing unbalanced codes. One such preferred set of codes is the Gold codes. Gold codes are particularly useful in a multi-user environment since a large number of these codes can be generated and only require one pair of feedback tap sets in a code

generating shift register. Yet, many of the Gold codes are unbalanced and would be unsuitable for many applications but for the code hopping features of the present invention. It will be further appreciated that
5 PN-codes may be generated with out particular regard to their balance characteristics since the code hopping features of the present invention will minimize the effects of unbalanced codes. Standard error correction circuitry may then be employed to rid the signal of the
10 deleterious effects caused by the unbalanced code. Thus, the code hopping feature of the present invention allows the dynamic generation of PN codes without having to first test the codes for acceptable balance.

15 Finally, orthogonal PN-code sets constructed using randomized Walsh-Hadamard matrices typically have P-1 balanced PN-codes and the all one's PN-code, which is unbalanced. In a system without a cover PN-code the all
20 one's PN-code is unused due to DC bias problems and large correlation with adjacent cell PN-codes. The unusable all one's PN-code reduces the available PN-codes and therefore the capacity of the cell is reduced. With PN-code hopping, users only use the all ones PN-code for a
25 symbol time or small time block. Thus, potential signal degradations due to adjacent cell interference and DC biasing problems is equivalent to the symbol time or time block the user is using the all ones PN-code and easily corrected using normal error control techniques; in this
30 manner the capacity of the system is improved by 1/P percent.

It should be understood that the foregoing description is only illustrative of the invention. Various alternatives and modifications can be devised by those skilled in the art without departing from the invention. For example, 5 PN-code hopping features of the present invention may be adapted to mitigate in-band or sector interference. Accordingly, the present invention is intended to embrace all such alternatives, modifications and variances that fall within the scope of the appended claims.